Smoking behaviour in social networks

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Abstract

Many types of risky behavior involve significant behavioral complementarities (peer effects), and exert externalities on others. Typically, both peer effects and externalities flow on social and relational ties, such as family, friendship and workplace ties. To varying degrees, agents may be aware of the externality they exert on their neighbors, and care about the associated welfare effect. In this paper we adapt the linear-quadratic framework of Ballester et al. (2006) for the analysis of peer effects on networks to allow for the presence of external effects and altruism. We find that the network density affects the amount of risky behavior in a non monotonic fashion, increasing for small densities and decreasing afterwards. This qualifies the usual conclusions that risky behavior increases in denser networks due to peer effects alone. We also find that clustering agents according to their preferences for the risky behavior has non monotonic impacts on the polarization of risk and on aggregate risk, with maximum risk occurring for moderate levels of clustering. Finally, we show that in non regular network architectures, more central agents do not necessarily adopt more risky behaviour due to altruism. In terms of policy implications, we find that policies that target the degree of altruism are more efficient in densely connected networks, where the non linear effect of altruism takes over the linear peer effects.

1 Introduction

There is an increasing awareness in health policy that health related behaviour is affected by the structure of social relations. The habits of acquaintances are in fact crucial in determining people behaviour even when this implies health hazards, through the so-called 'peer effects', that pervade many types of social interaction. These effects appear to be particularly important for smoking decisions, where behaviour is strongly correlated at small distances in the network, due to various psychological and sociological forces stemming from emulation, group acceptance, identity, and so on. Such an evidence cannot be ignored when designing public interventions, given social interactions amplify the effect of public policies via the 'social multiplier' (Glaeser et al., 2003) mechanism. In addition, the increasing importance of smoking related diseases and their burden on national health budgets (see Sloan et al., 2004) motivate more empirical and theoretical research.

Empirically the existence of a strong correlation between behaviours of individuals belonging to the same group of friends is not controversial and it goes far beyond the first degree of separation, thus meaning that the entire structure of the network matters. Evidence of such a correlation has been found in teenage pregnancies[1] (Evans et al., 1992), human feelings such as depression (Rosenquist et al., 2010a), loneliness (Cacioppo et al., 2009), happiness (Fowler and

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[1]Even if the peer effect disappears when a two equations model is used.

Christakis, 2008) as well as in health behaviours e.g drug use (Mednick et al., 2010), alcohol consumption (Clark and Loheac, 2007), obesity (Christakis and Fowler, 2007; Ali et al., 2011), cohoperative behaviour (Fowler and Christakis, 2010) and smoking (Christakis and Fowler, 2008). Christakis ad Fowlers's paper focus on the spread of smoking cessation. They follow the individuals interviewed in the Framingham Heart Study from 1971 to 2003 and they find that smokers move from the centre to the periphery of the network, thus decreasing their own eigenvalue centrality[2] across time. In addition, the spread of smoking cessation is more effective in the clusters of high educated individuals and it takes place via social rather than geographic distance. Another clear empirical finding is the presence of clusters of smokers in the social network (Christakis and Fowler, 2008; MacD.Hunter et al., 1991). Further evidence on the importance of peer effects is provided by Jones (1994), who estimates a double hurdle model of smoking cessation and finds that social interactions, measured by a variable indicating the presence of another smoker in the household, is a good prediction of quitting smoking. Norton et al. (1998) finds that a positive peer effect is present even if endogenous sorting is corrected using a two steps probit regression. Peer effects, in particular at the school level, seem to be crucial in the determination of risky behaviours when we consider adolescents (Powell et al., 2005). For such a reason the analysis carried out by Clark and Loheac (2007),[3] suggests that targeting a 'heavy smoking group' (e.g. a school) would be more effective than targeting two groups characterized by half of the prevalence of cigarette consumption. Strong school level peer effects in drug use, smoking and alcohol consumption are also found by Gaviria and Raphael (2001), and evidence of endogeneity bias is just present in drug and alcohol consumption. On the contrary, just a weak effect of social interaction on risky behaviour is observed by Soetevent and Koreman (2007). The presence of positive peer effects is found to be robust to the use of instrumental variables and the introduction of school fixed effects (Fletcher, 2010), while in other cases it disappears when endogeneity is taken into account (Cutler and Glaeser, 2010a). However a 'social multiplier effect' is still present (Cutler and Glaeser, 2010a). One of the empirical challenges in studying the importance of peer effects is distinguishing between the effect of influence vs the one of selection (see Kirke, 2004; Hall and Valente, 2007)[4]. Mercken et al. (2010) find that selection is more important than influence, but that both effects decrease over time. On the contrary, according to Steglich et al. (2010), the importance of influence decreases over time while the one of selection remains pretty stable.

Even if the theoretical literature on smoking is well developed, it just considers the choice of smoking as result of an individual maximization process and social interactions have just started been analyzed (see Cawley and Ruhm, 2011, for a recent review). One of the only papers that explicitly account for social interaction is Poutvara and Siemers (2008) who study the effect of the introduction of a smoking ban on the prevalence of smoking and Cutler and Glaeser (2010a) who sketch a model of smoking with peer effects.

In economics, models that study peer effects within a social network of relations exist, but they do not incorporate important features of risky behaviours. Our theoretical model is based on the framework proposed by Ballester et al. (2006) which has been applied so far to the analysis of criminal networks (Ballester et al., 2006) and education (Calv-Armengol et al., 2009).

Data from the Health survey of England 2007, contained in table .., show that the main reason for quitting smoking is the presence of actual and future health problems (around 25% of the answers), but more than 10% of the answers indicated that people quitted smoking because of altruistic reasons (passive smoke on children, adults, fetuses). To account for such a stylized fact, besides the positive peer effect on smoking intensity, we thus introduce a direct negative

[2]For an analysis on how to detect central individuals in the social network, see Christakis and Fowler (2010)

[3]In the paper endogeneity in friends selection and unobserved heterogeneity in schools are taken into account

[4]Such a classification is similar to **?**'s one. ie. the individuals belonging to the same group behave in the same way because of the so called 'endogenous' effects, 'exogenous (contextual)' effect or correlated effects. According to Manski (1993) just the first effect ('endogenous effect' or 'influence') creates the social multiplier.

externality (second-hand smoke) that decreases the individual returns to smoking if we assume that people are altruistic (see Cutler and Glaeser, 2010a, for a qualitative explanation of the phenomenon). The inclusion of passive smoke in the model is due to the growing evidence of its negative effect on health (see, for example, Law et al., 1997a; He et al., 1999; Otsuka et al., 2001; Wincup et al., 2004) that are on the basis of the introduction of smoking bans in many countries in the World. Failing in considering such a dimension means not taking into account a fondamental ingredient of the decision of smoking.

Reason for quitting smoking	**% of the answers**
Advice from a GP and health professional	4,62%
Advert for a nicotine replacement product	0,13%
Government, TV, radio or press advert	1,15%
Hearing about a new stop smoking treatment	0,34%
Financial reasons	9,66%
Smoking ban	0,68%
I knew somebody else who was stopping	1,67%
Saying a health warning on a cigarette packet	1,17%
Family or friends wanted me to stop	9,14%
Being contacted by my local NHS stop smoking service	0,13%
Health problems I had at that time	9,56%
Worried about future health problems	14,80%
Pregnancy	4,49%
Worried about effects on my children	5,06%
Worried about effects on other family members	2,87%
My own motivation	24,07%
Something else	9,29%
Cannot remember	1,17%
Total	100,00%

We find a not monotonic effect of the density of the network on the equilibrium quantity of smoking, given the impact of the peer effect is at some point counterbalanced by the effect of second-hand smoke. Moreover, the effect of different anti-smoking policies depends on the degree in the same fashion and the network structure can determine which one is the most effective. Furthermore, the homophily rate of the network does not change the total quantity of smoking in the population, but it influences the difference in smoking intensity between individuals who receive personal high benefits from smoking and individuals who receive low personal benefits. Our model predicts that more polarized networks not necessarily predict more polarization in smoking intensity, due to the effect of second order neighbors. In a context of simmetric networks and heterogeneous agents we are able to derive some insights on the effects of policies that affects the social networks (e.g smoking bans) and policies that leave the social relationships unaffected (e.g. taxation). Finally, we find a characterisation of the key smoker in terms of Bonacich's incentrality and we are able to identify the key smoker.

The paper is structured as follows. Section 2 presents the model. In section 3 we restrict our analysis to a regular networks. Finally, section 4 generalizes the findings considering an irregular network structure. Section 5 concludes.

2 The Model

Consider a set of n agents organized in a social network $\mathbf{g}$, defined by a matrix $\mathbf{G}$ whose generic element $g_{ij} \in \{0,1\}$ measures the presence of a social tie (or link) between agents i and j. We call i and j "neighbours" whenever $g_{ij} = 1$. Note that the network is symmetric, that is $g_{ij} = g_{ji}\ \forall\ i, j \in \mathbf{g}$. We also assume that $g_{ii} = 0,\ \forall i$.

Each agent i chooses her smoking intensity $x_i \in \mathbb{R}$, and derives the following utility as a function of the vector $\bar{x} \in \Re^n$ of all smoking activities in the network:

$$U_i = \alpha_i x_i + \sum_{j\in N} g_{ij} x_i x_j - \gamma_1 \delta\left[\gamma_0 x_i^2 + (\sum_{j\in N} g_{ij} x_j + x_i)^2\right] - \gamma_2 \delta \sum_{j\in N} g_{ij}[\gamma_0 x_j^2 + (\sum_{k\in N} g_{jk} x_k + x_j)^2] \quad (1)$$

The first block of the utility function captures the private enjoyment of smoke, which can differ across agents (when $\alpha_i \neq \alpha_j$) and may include costs that are proportional to the smoking intensity, e.g. cigarette prices[5].

The second term captures the relational aspect of smoking. Here, the extent to which agents enjoy smoking increases in the smoking intensity of i's neighbours. This linear specification is in line with the peer effect model of local complementarities (as in Ballester et al. (2006)).

The third term captures the negative health effects of smoking, mapping the vector of all smoking intensities in the network into the perceived health damage for agent i. This cost part of the utility function takes into account the direct effect of i's smoking activity on i's own health ($\gamma_0 x_i^2$), as well as the effect of the total stock of smoke emitted by i's neighbors, $(\sum_{j\in N} g_{ij} x_j + x_i)^2$, i.e, the so-called passive smoke. The parameter γ_1 quantifies the response of an agent's utility to changes in her health conditions, γ_0 allows the effect of active smoke to differ from that of passive smoke, while δ quantifies the general awareness of health damages caused by smoke. The shape of the cost function is consistent with Doll and Peto (1978) prediction of a quadratic damage caused by cigarette consumption in the multistage model of carcinogenesis (Armitage and Doll, 1954). In addition, a convex cost function is also assumed by Cutler and Glaeser (2010a). These costs can be intended as a measure of risk of smoking related diseases affecting agents. We are using the network $\mathbf{g}$ as an approximation of the patterns of passive smoke, although these patterns may in principle differ from the relational ties described by $\mathbf{G}$.

Finally, agents care about the health damage of their direct neighbors caused by smoking. This may reflect a feeling of "altruism", as well as some sort of monetary costs in the form, for instance, of cost sharing of health expenditure at society level. We measure the importance of altruism through the term γ_2, expressing the response of utility to an increase in the negative health effect of smoking affecting neighbors.

We factorize the various blocks of the utility function so to isolate those terms that depend linearly on agent i's action, those that depend on the square of agent i's action, those that depend on the product of agents i and j's actions and those independent from i's actions. We have denoted by $g_{ik}^{[2]}$ the generic term of the squared matrix $\mathbf{G^2}$, identifying the number of paths of length two from node i to node j (see Appendix A for detailed computations):

$$U_i = \alpha x_i - [\delta(\gamma_1(1+\gamma_0) + \gamma_2 \sum_j g_{ij}^2)] x_i^2 + (1 - 2\delta\gamma_1 - 2\delta\gamma_2) \sum_{j\in N} g_{ij} x_i x_j - 2\gamma_2 \delta (\sum_{k\neq i} g_{ik}^{[2]}) x_i x_k + h_{-i}, \quad (2)$$

where h_{-i} denotes the sum of all terms that in (1) do not depend on agent i's action x_i.

Letting $\Gamma_1 = 2\delta\gamma_1$ and $\Gamma_2 = 2\delta\gamma_2$, setting $d_i = \sum_j g_{ij}^2$ since $g_{ij} \in \{0,1\}$ for all ij and denoting by

$$\sigma_i = \Gamma_1(1+\gamma_0) + \Gamma_2 d_i$$

the coefficient that multiplies the square of agent i's action in (2), we rewrite (2) as follows:

$$U_i = \alpha x_i - \frac{1}{2}\sigma_i x_i^2 + (1 - \Gamma_1 - \Gamma_2) \sum_{j\in N} g_{ij} x_i x_j - \Gamma_2 (\sum_{k\neq i} g_{ik}^{[2]}) x_i x_k + h_{-i}, \quad (3)$$

First, the term $(1 - \Gamma_1 - \Gamma_2)$ acts as a modified peer effect term: the intensity of peer effect (here normalized to one) is reduced by two factors that are increasing in the perceived health

[5]This is possible since the utility function has a quasilinear form so that the linear coefficient α_i may include also linear costs.

damage from smoke δ and in γ_1 and γ_2, i.e. the perceived own and neighbors' health damage from passive smoke. Health concerns about smoke thus reduce the effects of the social and relational aspects on smoking, thereby counteracting the (positive) peer effect.

Second, the presence of altruism towards one's neighbors introduces new interdependences between distance-two neighbors in the network $\mathbf{g}$. Distance-two neighbors' actions are pure strategic substitutes, and further contribute to decrease the peer effect of a direct neighbor when this happens to also be a distance-two neighbor in the network (therefore, in case of clustering).

3 Regular Networks

In this section we study the case of regular networks, where all agents have the same degree d. We first focus on the case of homogeneous agents ($\alpha_i = \alpha_j = \alpha$ for all $i, j = 1, 2, ...n$). In such setting, the only relevant statistic about the network is the common degree d, and, given the homogeneity of agents, this will allow us to focus on symmetric equilibria.

3.1 Equilibrium Characterization with Identical Agents

Equilibrium smoking is characterized by the following first order condition for each agent i:

$$\alpha - \sigma_i x_i + (1 - \Gamma_1 - \Gamma_2) \sum_{j \in N} g_{ij} x_j - \Gamma_2 \sum_{k \neq i} (g_{ik}^{[2]}) x_k = 0. \tag{4}$$

In a symmetric equilibrium $x_i^* = x_j^*$ for all i, j. Moreover, since the network $\mathbf{g}$ is regular of degree d, then $\sum_{k \in N} g_{ik}^{[2]} = d(d-1)$. Using the expression for the term σ_i we can then rewrite (4) as follows:

$$\alpha - x^* [\Gamma_1 (1 + \gamma_0) - d(1 - \Gamma_1 - \Gamma_2) + \Gamma_2 d^2] = 0. \tag{5}$$

The social incentives to smoking result from the sum of the positive peer effects and of the negative health effects of active smoke and of passive smoke, both on oneself and on others, given by the term:

$$K \equiv [\Gamma_1 (1 + \gamma_0) - d(1 - \Gamma_1 - \Gamma_2) + \Gamma_2 d^2]. \tag{6}$$

When the term K in (6) is negative, incentives to smoke are strictly positive for any positive amount of smoke x. Since these incentives add up to the fixed positive incentive α, no positive amount of smoke is consistent with equilibrium.

Proposition 1 *Let $\mathbf{g}$ be a regular network with identical agents. Equilibrium smoking intensity is positive if and only if (6) is positive. The unique positive per capita equilibrium smoking intensity is given by:*

$$x^* = \frac{\alpha}{\Gamma_1 (1 + \gamma_0) - d(1 - \Gamma_1 - \Gamma_2) + \Gamma_2 d^2} \equiv \frac{\alpha}{K}. \tag{7}$$

Proposition 1 implies some parameters restrictions. When $\Gamma_1 + \Gamma_2 > 1$, equilibrium smoking intensity is always positive for all positive values of the other parameters, and in particular for all $d \geq 0$. In this case, the negative effect of passive smoke on smoking incentives dominates the peer effects, and any positive change in the degree would monotonically decrease the incentives of smoking. The case $\Gamma_1 + \Gamma_2 < 1$ adds interest to the model, since a change in the degree d has opposite effects on incentives through the net peer effect (still positive) and the effect of altruism. For this reason we will mainly refer to this latter case throughout the paper. Under this parameter range we have positive equilibrium smoking if $\Gamma_2 > \frac{(1-\Gamma_1-\Gamma_2)^2}{4\Gamma_1(1+\gamma_0)}$ (see Appendix B for details). The range of Γ_2 that satisfy this requirement is of the type $\Gamma_2 > \Gamma_2^*$ with $\Gamma_2^* < 1-\Gamma_1$. This can be obtained by considering that the function $(1-\Gamma_1-\Gamma_2)^2$ is convex in Γ_2, with a minimum at $1-\Gamma_1$.

3.2 Network density and smoking behaviour

Let us consider again equation (7). Taking the first derivative with respect to d we obtain:,

$$\frac{\partial x^*}{\partial d} = \frac{\alpha(1-\Gamma_1-\Gamma_2-2d\Gamma_2)}{K^2}.$$

The sign of the effect of smoke is determined by the following regions:

$$\begin{cases} d < \frac{1-\Gamma_1-\Gamma_2}{2\Gamma_2} & \Rightarrow \quad \frac{\partial x^*}{\partial d} > 0 \\ d = \frac{1-\Gamma_1-\Gamma_2}{2\Gamma_2} & \Rightarrow \quad \frac{\partial x^*}{\partial d} = 0 \\ d > \frac{1-\Gamma_1-\Gamma_2}{2\Gamma_2} & \Rightarrow \quad \frac{\partial x^*}{\partial d} < 0 \end{cases}$$

Note that when $\Gamma_1 + \Gamma_2 > 1$, smoking is always decreasing with network density and approaching zero for very large degrees. When instead $\Gamma_1 + \Gamma_2 < 1$, smoking follows a non monotonic pattern, reaching a maximum for $d^{max} = \frac{1-\Gamma_1-\Gamma_2}{2\Gamma_2}$. Before d^{max}, smoking increases with network density as a result of the prevailing force of the net peer effect; after d^{max}, smoking monotonically decreases as a result of altruism, and tends to zero for very large degrees. Note also that, if $\Gamma_1 < 1$, then d^{max} is always decreasing in both Γ_1 and Γ_2.

Proposition 2 *Let* $\mathbf{g}$ *be a regular network with identical agents. When* $\Gamma_1+\Gamma_2 \geq 1$*, equilibrium smoking intensity always decreases with the degree. When* $\Gamma_1 + \Gamma_2 < 1$*, equilibrium smoking intensity is a non monotonic function of the degree, increasing for low degrees* ($d < d^*$) *and decreasing for high degrees* ($d > d^*$)*. The degree at which smoking is maximal decreases with health concerns.*

Compared to the traditional analysis of peer effects in networks, where a "social multiplier" captures the positive and monotonic relation between network density and smoke (see Glaser....), the non monotonic effect obtained here highlights the presence of direct and indirect strategic interactions in a given network. Here, in fact, an increase in the degree affects smoking through the growth of an agent's direct neighbors (at a constant rate of 1), exerting the net peer effect $(1-\Gamma_1-\Gamma_2)$, and through the growth of neighbors of distance two (at a rate of $2d$), who exert a negative externality on the agent's neighbors, affecting utility at the rate Γ_2. As d grows, this second effect becomes larger and eventually takes over, implying a decrease in overall smoking intensity. This non monotonicity can be understood also looking at the first order conditions in (5). A marginal change in d modifies the (dis)incentives to smoking (K), and therefore the value of x^* that is compatible with equilibrium. In particular, when K increases in d then x^* has to decrease in d. The opposite happens when K is decreasing in d. If $\Gamma_1 + \Gamma_2 < 1$, K is a non monotone convex function of d, so that x^* needs to be a non monotone concave function of d. By similar arguments, when $\Gamma_1 + \Gamma_2 > 1$, K is an increasing function in d so that x^* is monotonically decreasing in d. Figure 1 gives a graphical representation of the relationship between equilibrium smoking intensities and the degree for different levels of γ_2 and, thus, for different shapes of K.

3.3 Anti-smoking policies and the role of the network

We use the above equilibrium characterization to assess how changes in the parameters of the utility function (1) affect the level of smoking and health risk. Each of these parameters can be

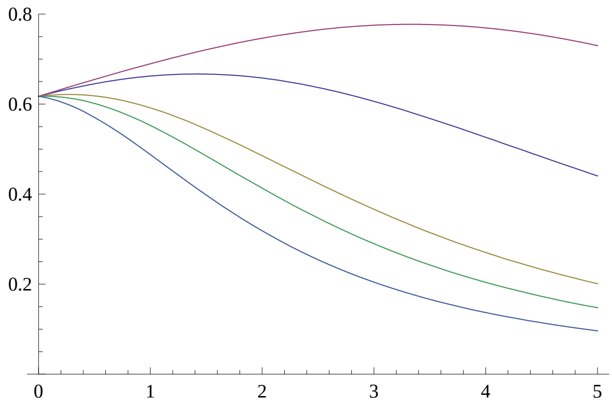


Figure 1: Equilibrium Smoke and Degree ($\alpha = 2,\ \delta = 0.3,\ \gamma_0 = 5,\ \gamma_1 = 0.9$)

targeted by specific anti-smoking policies, affecting either the (private dimension of) preferences for smoking (α), the general awareness of the health damages caused by smoke (δ), and in particular by active smoke (γ_0), the concern for one's own health (γ_1) and for one's neighbors' health (γ_2).[6]

Let us first consider the change in the level of smoking induced by a marginal change in the parameters γ_1 and γ_2, measured by the terms $\frac{dx^*}{d\gamma_1}$ and $\frac{dx^*}{d\gamma_2}$, respectively. The following condition can be shown to hold (see appendix C for derivations of this and other conditions in this section):

$$|\frac{\partial x^*}{\partial \gamma_1}| > |\frac{\partial x^*}{\partial \gamma_2}| \Leftrightarrow \gamma_0 + d + 1 > d^2 + d.$$

This tells us that when the network is very densely connected, the effect of a marginal increase in agents' concern for their neighbors' health (altruism) has a larger impact on total smoking than a change in their concern for their own health. This is due to the role of the degree in shaping incentives to smoke: in a symmetric equilibrium, a large degree amplifies the perceived marginal damage of one's smoking on one's neighbors' health, which is assumed to be affected by the smoke of a large number of neighbors. This quadratic effect of degree on incentives implies that for large degrees the effect of altruism tends to dominate that of concerns for one's self. This mechanism carries over if one measures the percentage change in smoking induced by percentage changes in the parameters, given by the following elasticity indices:

$$\epsilon_{\gamma_1} = -\frac{\Gamma_1(1 + d + \gamma_0)}{K};$$

$$\epsilon_{\gamma_2} = -\frac{\Gamma_2 d(1 + d)}{K};$$

where it is clear that for large enough degrees the term ϵ_{γ_2} tends to dominate in absolute magnitude. The main insight in terms of policy implications is that keeping constant and equal the effect of a dollar invested in policies that target either altruism or self concern, that dollar would more effectively reduce smoking when invested in altruism if the network is dense, and when invested in self concern if the network is sparse.

Another interesting comparison is between changes in the general perception of the health damages of smoke (the parameter δ) and the degree of altruism. Policies that target these two aspects of preferences may differ substantially, the first focusing on scientific and upsetting

[6]Coherently with the previous analysis we will consider parameters such that a positive smoke quantity in equilibrium is ensured.

evidence of the consequences of heavy smoke, the second stressing the externality of our own behavior on people we care about. In our formal model, the comparison is between the terms $\frac{dx^*}{d\delta}$ and $\frac{dx^*}{d\gamma_2}$. We obtain the following condition:

$$|\frac{\partial x_i}{\partial \delta}| > |\frac{\partial x_i}{\partial \gamma_2}| \iff d^2(\gamma_2 - \delta) + d(\gamma_1 + \gamma_2 - \delta) + \gamma_1(1 + \gamma_0) > 0$$

As we discuss in Appendix C, this condition implies that a marginal change in γ_2 may be more effective than a marginal change in δ when both δ and d are large and γ_2 is small. The insight behind this result contains some interesting policy implications. To fix ideas, let us look at the effect of increasing δ: a larger awareness of smoking related risks would increase the sensibility to one's own smoke exposure and to one's neighbors' smoke exposure. In particular, the latter would change by a rate given by γ_2 - the intensity by which I actually care about my neighbors' health. So, when γ_2 is small, any change in δ brings about little changes in the way agents react to their neighbors' health damage: increasing awareness has little consequences on the way we value our neighbors health damage if we don't care about them. All this implies that when the potential effects of altruism on smoking are large (large d), policies that directly target altruism may be more effective than policies that increase the awareness of smoke related risks, even if the latter would at the same time increase concerns for one's own health.

These consideration only apply when we measure the absolute effect on smoke; the largest percentage abatement in smoking is in fact always induced by a change in the general awareness (δ) of smoke damages, as the following relation makes clear:

$$\epsilon_\delta = -\frac{\Gamma_1(1 + d + \gamma_0) + \Gamma_2 d(1 + d)}{K} = \epsilon_{\gamma_1} + \epsilon_{\gamma_2}.$$

We summarize these findings and some additional properties of the marginal effects studied above in the following proposition:

Proposition 3 *Let* **g** *be a regular network with identical agents.*

1) The effect of a marginal change in parameters γ_1, γ_2 and δ on equilibrium smoke is a non monotonic function of the degree, with a magnitude that increases for low degrees and decreases for high degrees;

2) For large degrees, both the absolute and the percentage reduction of smoke induced by an increase in γ_2 are larger than those induced by an increase in γ_1;

3) For large enough values of d and δ and for low values of γ_2, the absolute reduction of smoke induced by an increase in γ_2 is larger than that induced by an increase in δ;

4) The percentage reduction of smoke induced by an increase of δ is equivalent to the combined effect of increases in γ_1 and γ_2.

Proof. See Appendix C. ■

We can rephrase the above proposition in terms of policy recommendation. Point 1) tells us that the effectiveness of anti-smoking policies is affected by the degree of the network: absolute effects are largest at medium densities, while percentage reductions are largest in sparse networks. Points 2) and 3) tell us that in very dense networks, targeting altruism and the awareness of the externalities of people's own smoking on their neighbors' health tend to be more effective than targeting people's awareness of smoke related risks in general and/or people's care for their own health. Point 4) specifies that this only applies to absolute smoke reduction, while policies that target percentage reductions should always focus on the general awareness of smoking related risks.

3.4 Heterogeneous Agents: Homophily, Segregation and their Effects on Smoking

So far we have abstracted from any heterogeneity in agents' taste for smoke by assuming that the parameter α is the same for all agents. Such heterogeneities are important for the very formation and distribution of social connections across agents. First of all, agents with similar preferences may tend to form ties more often than dissimilar agents do, a pervasive phenomenon that is know as "homophily" in sociology, psychology and economics (see McFadden,... for an inclusive survey). The correlation between smoking habits and social interaction can be reinforced by specific policies, such as the establishment of smoking areas and/or smoking bans, which favor the formation of links between smokers and between non smokers. Although it is still largely controversial whether the observed correlation should be taken as evidence of peer effects or rather of assortative matching, there seems to be wide agreement about the relevance and pervasiveness of homophily in smoking (see Christakis and Fowler, 2008). In this section we take the simple route of assuming a certain rate of homophily that operates along the dimension of preferences for smoking, measured by the parameter α. We are interested in assessing the relation between homophily and smoking polarization, taking into account the endogenous effect of different segregation patterns on smoking behavior. We will also look at how this relation changes with the average degree of the network. From a policy point of view, given the assumed convexity of the damage that smoke exerts on health, different distributions of smoking intensities across agents may have very different welfare consequences, even for the same aggregate smoking prevalence.

We assume that agents come in two typologies: those with high preferences for smoke α^H and those with low preferences for smoke α^L with $\alpha^H > \alpha^L$. We then define by $q \in [0,1]$ the *homophily rate* of the network, i.e. the share of same type neighbors that an agent has in the network. Note that we assume that q is type invariant and, for consistency with regularity of the network, that the populations of the two types are of equal sizes. Each agent has (dq) neighbors of own type and $d(1-q)$ neighbors of different type. For an agent i of type t, with $t = \{H, L\}$, the following facts hold:

- dq is the number of i's neighbors of type t;
- $d(1-q)$ is the number of i's neighbors of type different from t;
- $dq(dq-1)$ is the number of agents of type t connected with i's neighbors of type t;
- $d(1-q)[d(1-q)-1]$ is the number of agents of type t connected with i's neighbors of type different from t;
- $dqd(1-q)$ is the number of agents of type different from t connected with i's neighbors of type t;
- $d(1-q)dq$ is the number of agents of different from t connected with $i's$ neighbors of different from t.

The type-symmetric equilibrium levels of smoke for types H and L are given by (see appendix for derivations):

$$\begin{cases} x^H = \frac{1}{2}\left[\frac{\alpha^H+\alpha^L}{\Gamma_1(1+\gamma_0)-d(1-\Gamma_1-\Gamma_2)+\Gamma_2 d^2} + \frac{\alpha^H-\alpha^L}{\Gamma_1(1+\gamma_0)+\Gamma_2 d^2(1-2q)^2+d(1-2q)(1-\Gamma_1-\Gamma_2)}\right] \\ x^L = \frac{1}{2}\left[\frac{\alpha^H+\alpha^L}{\Gamma_1(1+\gamma_0)-d(1-\Gamma_1-\Gamma_2)+\Gamma_2 d^2} + \frac{\alpha^L-\alpha^H}{\Gamma_1(1+\gamma_0)+\Gamma_2 d^2(1-2q)^2+d(1-2q)(1-\Gamma_1-\Gamma_2)}\right] \end{cases} \tag{8}$$

Note that equilibrium smoking is the sum of two terms. The first term does not depend on homophily and is common to both types. It coincides with the equilibrium quantity under the assumption of homogenous agents with average preferences $\frac{\alpha_H+\alpha_L}{2}$. The second term measures how smoking of each type is spread around the mean. The symmetric spread around the mean - a direct consequence of the extreme symmetry of the problem - implies that the average quantity of equilibrium smoke is not affected by the homophily rate. This simple symmetric setting is therefore not fit to investigate the effect of homophily on aggregate smoking prevalence. However, the spread itself is interesting since it may not be monotonically related to homophily; this is shown in Figure 2, where the spread is increasing for low q and decreasing for high q, reaching its maximum at $\bar{q} = \frac{1-\Gamma_1-\Gamma_2(1-2d)}{4d\Gamma_2} > \frac{1}{2}$. Such non monotonic relation holds for large enough degrees, in particular when smoking is a decreasing function of the degree itself. These results are summarized in the proposition 4 (see Appendix E for the proof):

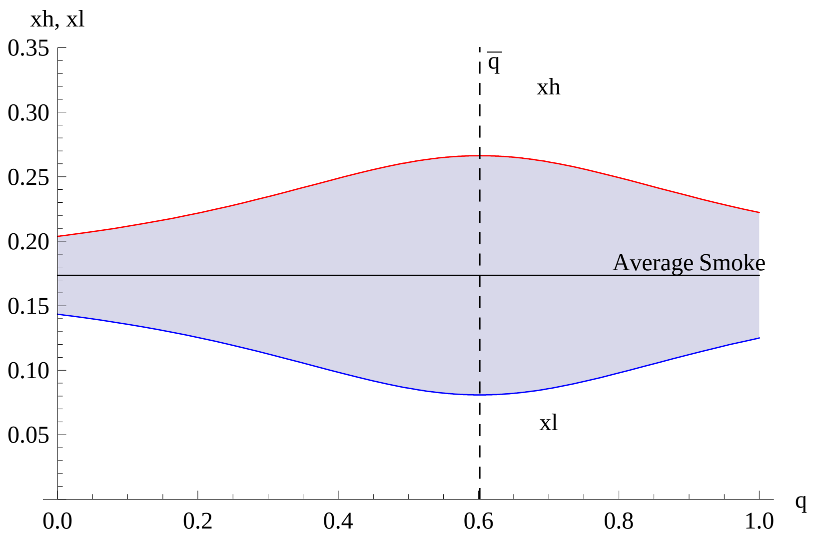


Figure 2: Spread: Parametrization: $\gamma_0 = 5$, $\gamma_1 = 0.5$, $\gamma_2 = 0.45$, $\delta = 0.33$, $\alpha^H = 0.8$, $\alpha^L = 0.4$, $d = 3$

Proposition 4 *In a regular network with identical populations of agents with high and low preferences for smoking, high preference agents always smoke more then low preference ones. When $d < d^*$, the spread between x^H and x^L is monotonically increasing in q, where d^* is as in proposition 1. When $d > d^*$, the spread is non monotone in q, reaching its maximum at $\bar{q} \in (1/2, 1]$, where $\bar{q}$ is decreasing in Γ_1, Γ_2 and d. Moreover, the maximal spread is independent of the degree.*

The non monotonic relation between homophily and equilibrium spread suggests that differences in smoking behavior may not always increase with the degree of segregation of agents according to their preferences for smoking. It is clear that such non monotonic relation could not hold in a model of pure peer effects (that is, with $\gamma_2 = 0$), in which case clustering H type agents would unambiguously increase their equilibrium smoking and decrease smoking of L type agents. It is also clear from the expression of $\bar{q}$ that the presence of smoke externalities and of convex damages cannot, alone, imply this non monotone relation, since $\bar{q} > 1$ for very low levels of Γ_2. We obtain some insight into the role of altruism by considering the various forces at work when we increase the degree of homophily q. At low levels of q, H agents are mainly surrounded by L agents and *viceversa*. Thus the stock of passive smoke experienced by H agents is likely to be low, while the smoke experienced by their neighbors (mainly L agents) is likey to be high (and mainly in the form of passive smoke). An increase in q changes the incentives to smoke of H agents due to two separate effects: the peer pressure from increased H type neighbours, and the marginal damage on own and neighbors' health. In this second respect, the new H type neighbors (experiencing less passive smoke and therefore in the flatter part of the damage function) replace L type neighbors (in the flatter part of the damage function), and incentives to smoke increase as a result. Specular arguments suggest that the opposite happens for L agents, whose smoking level decreases as a result of increases in q. As q keeps growing, these effects tend to weaken, with H agents surrounded by more and more H neighbours, who are exposed to larger and larger marginal damages from smoking. Eventually, for large enough q the net effect is reversed, and H type decrease their smoking intensity, while L type smoke more.

Below we provide a numerical example where we compute the spread between H and L agents as a function of q. Figure 3 shows regular networks of 8 nodes with $d = 3$. In figure 3a-c The homophily rate is, respectively, $q = \frac{1}{3}$, $q = \frac{2}{3}$ and $q = 1$, so that different distributions of types among nodes are shown.

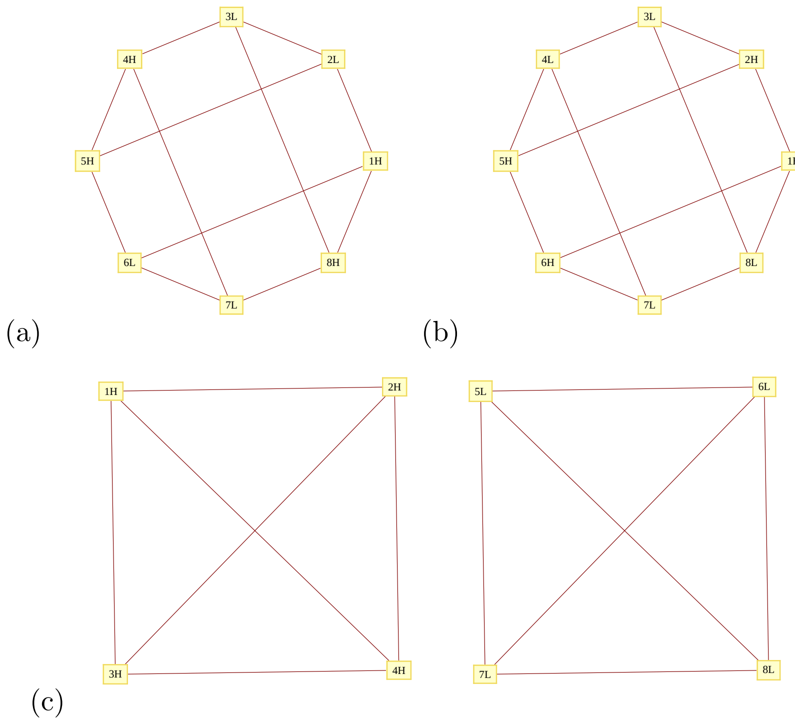


Figure 3: Networks with different degrees of homophily

Table 4 reports values of numerical simulations for the previous graphs.

Table 1: Homophily and Smoke Polarization

Network	**Homophily rate**	x^H	x^L	**Spread**	**Tot. Smoke**	**Total Risk**
3a	0.33	0.24	0.09	0.15	1.32	3.96
3b	0.66	0.27	0.06	0.21	1.32	4.36
3c	1	0.23	0.11	0.12	1.32	4.35

Parametrization: $\gamma_0 = 5$, $\gamma_1 = 0.5$, $\gamma_2 = 0.45$, $\delta = 0.33$, $\alpha^H = 0.8$, $\alpha^L = 0.4$

As we already noticed, homophily does not change the total smoking prevalence in the network, but it does change the distribution of active and passive smoke across agents. This change has an effect on the aggregate risk of illness in society, given the non linearity of individual risk. Aggregate risk figures are reported in the last column of table 4, computed as the sum of all

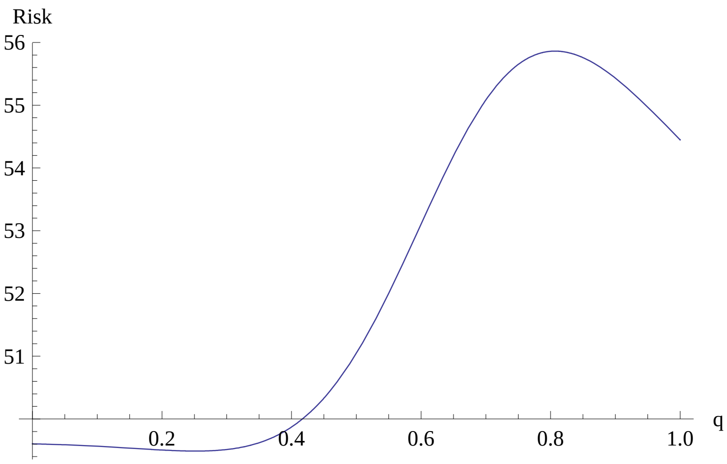


Figure 4: Aggregate Risk: Parametrization: $\gamma_0 = 5$, $\gamma_1 = 0.5$, $\gamma_2 = 0.45$, $\delta = 0.33$, $\alpha^H = 0.8$, $\alpha^L = 0.4$, $d = 3$

the individual risks - the sum of the active and passive smoke as specified in the utility function by the term $\left[\gamma_0 x_i^2 + (\sum_{j\in N} g_{ij}x_j + x_i)^2\right]$. Figure 4 depicts the non monotone relationship between level of homophily and aggregate risk. The level of homophily that maximizes risk is not 1, and is in general different from $\bar{q}$, i.e. the value that maximizes the spread. Since public health expenditure is related to the risk of illness, this result is of some relevance in terms of effect on public health policies. In particular policies such as smoking bans affect the distribution of smokers in the network and the degree of homophily. This has consequences on the distribution of equilibrium smoking, on aggregate risk and, finally, on public health expenditure.

4 Generic Networks

Our analysis of regular networks has focused on the role of the degree d in agents' decisions to smoke. Moving now to non regular networks allows us to address new issues, such as the relation between the position of an agent in the network and her smoking intensity, and how properties of the network architecture affect the aggregate smoking prevalence. We will also ask which agents in the network the policy maker should most efficiently target, given their preferences and their position in the network.

4.1 Equilibrium Characterization

The first order conditions defining the equilibrium vector of smoking intensities $\bar{x}$ are written in the following matrix form, where each line refers to a specific agent:

$$\bar{\alpha} = \left[\beta I - (1 - \Gamma_1 - \Gamma_2)G + \Gamma_2 G^2\right]\bar{x}.$$

where we have defined

$$\beta \equiv \Gamma_1(1 + \gamma_0).$$

Dividing by β and factorizing terms we obtain:

$$\frac{1}{\beta}\bar{\alpha} = \left[I - \frac{(1 - \Gamma_1 - \Gamma_2)}{\beta}\left(G - \frac{\Gamma_2}{1 - \Gamma_1 - \Gamma_2}G^2\right)\right]\bar{x}.$$

Let us first consider the case of no altruism $\Gamma_2 = 0$. FOCs are simply given by:

$$\frac{1}{\beta}\bar{\alpha} = \left[I - \frac{(1-\Gamma_1)}{\beta}G)\right]\bar{x}.$$

As first shown by Ballester et al. (2006), the equilibrium vector $\bar{x}$ is here characterized by the vector of Bonacich centralities of the network G with discount factor $\frac{(1-\Gamma_1)}{\beta}$. This vector is given as follows:

$$b\left(\frac{1-\Gamma_1}{\beta}, G\right) = \left[I - \frac{1-\Gamma_1}{\beta}G\right]^{-1}\bar{1}$$

where the above inverse is assumed to exist.

With altruism, the relevant matrix on which to operate the above inversion is $\tilde{G}$, defined as $\tilde{G} \equiv G - \frac{\Gamma_2}{1-\Gamma_1-\Gamma_2}G^2$. Note, however, that $\tilde{G}$ typically contains negative entries. In fact, the elements of the matrix $\tilde{G}$ account for the strategic interaction that altruism generates between nodes that are at distance 2 in the network (even if not directly connected). In particular, each given element $\tilde{g}_{ij}$ is made of two parts: the net peer effect (which is zero if i and j are not linked in G and equals 1 otherwise), and the term $\frac{\Gamma_2}{(1-\Gamma_1-\Gamma_2)} \cdot g_{ij}^{[2]}$ which expresses the strategic substitutability between i and all agents that are neighbors of both i and j in G. The exact relationship between G and $\tilde{G}$ is as follows (see also figure 5).

$$\tilde{g}_{ij} = \begin{cases} 0 & \text{if } g_{ij} = 0 \text{ and } g_{ij}^{[2]} = 0 \\ 1 & \text{if } g_{ij} = 1 \text{ and } g_{ij}^{[2]} = 0 \\ -\frac{\Gamma_2}{(1-\Gamma_1-\Gamma_2)}g_{ij}^{[2]} & \text{if } g_{ij} = 0 \text{ and } g_{ij}^{[2]} > 0 \\ 1 - \frac{\Gamma_2}{(1-\Gamma_1-\Gamma_2)}g_{ij}^{[2]} & \text{if } g_{ij} = 1 \text{ and } g_{ij}^{[2]} > 0 \end{cases}$$

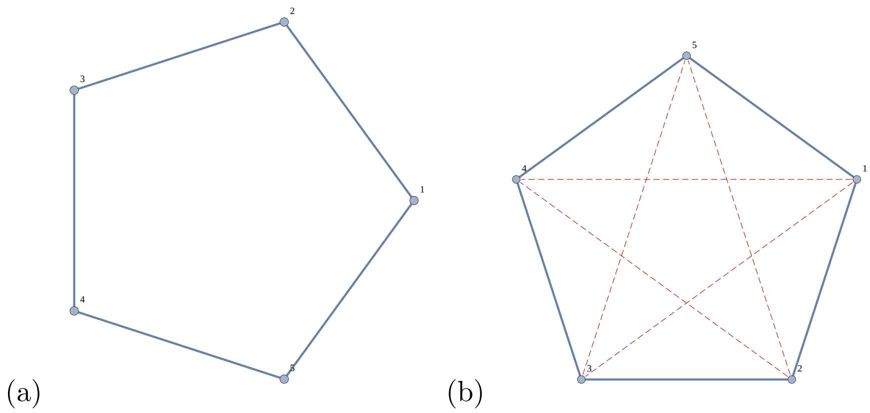


Figure 5: G and $\tilde{G}$

We now provide some examples of different networks G and the implied equilibrium smoking quantities. For each network G we first consider the case of $\Gamma_2 = 0$ and then of $\Gamma_2 > 0$. The first case can be considered a benchmark case in where there are no second order effects and C is equivalent to G.

In a model without altruism the players who smoke the most are the most connected (i.e. 2,6,11,7), while the peripheries have a lower centrality. When altruism is added to the model ($\gamma_2 > 0$) second order links become crucial. In fact, the least central and the one who smokes the least is player1, who has the greatest number of second order links, given it is connected with all the other players in the network.

Moving from network 1 to network 3 implies keeping the number of nodes constant (n=5) while increasing the network density by adding new links connecting the peripheric players. In

Table 2: Networks Comparisons without Altruism ($\gamma_2 = 0$)

Network	**Players**	b^i	x^*	**Tot.** x^*
Star	1	1.23	0.07	
	2-5	1.06	0.06	0.33
Papillon	1	1.24	0.07	
	2-5	1.12	0.06	0.35
Connected Star	1	1.26	0.077	
	2-5	1.19	0.073	0.37

Parametrization: $\gamma_0 = 20$, $\gamma_1 = 0.7$, $\delta = 0.33$, $\alpha = 0.6$

Table 3: Networks Comparisons with Altruism ($\gamma_2 = 0.25$)

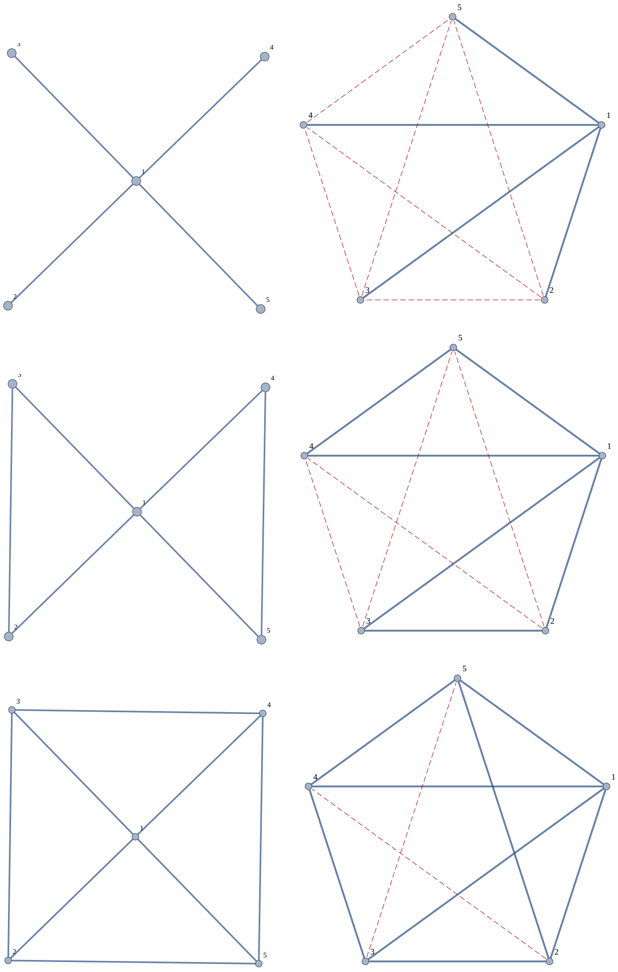
Network	**Players**	b^i	x^*	**Tot.** x^*
Star	1	1.62	0.065	
	2-5	1.47	0.059	0.304
Papillon	1	1.51	0.061	
	2-5	1.46	0.059	0.300
Connected Star	1	1.398	0.058	
	2-5	1.393	0.057	0.28

Parametrization: $\gamma_0 = 20$, $\gamma_1 = 0.7$, $\gamma_2 = 0.25$, $\delta = 0.33$, $\alpha = 0.6$

Table 4: Ballester et al. (2006) case

Γ_2	**Players**	b^i	x^*	**Tot.** x^*
$\gamma_2 = 0$	1	1.29	0.079	
	2,6,7,11	1.35	0.082	
	3,4,5,8,9,10	1.28	0.078	0.88
$\gamma_2 = 0.25$	1	4.25	0.051	
	2,6,7,11	4.34	0.052	
	3,4,5,8,9,10	4.40	0.053	0.57

Parametrization: $\gamma_0 = 20$, $\gamma_1 = 0.7$, $\gamma_2 = 0.25$, $\delta = 0.33$, $\alpha = 0.6$



(a) (b) (c)

Figure 6: Asymmetric Network

the case of $\gamma_2 = 0$ $b^i_\alpha = x^*$, because in the original network $\mathbf{g}$ all the quantities are perfect complements. In addition, $g = \tilde{g}$ so the model is equivalent to a model with peer effects and no externalities (see **?**). In this setting, the Bonacich centrality of every player increases when the network density increases. Every link is positive so their addition increments the number of paths passing trough each agent. Such increase is greater for peripherical nodes, since connecting the peripheries adds to the central player just links of distance two, which are discounted at a λ rate. When we consider a model with altruism and negative externalities adding a first order link creates also a greater number of (negative) second order ones, which counterbalance the positive peer effect. Note that the Bonacich centrality follows the same non monotonic behaviour found in the symmetric case. In addition, in more connected networks the difference in smoking intensities between the center and the peripherical agents tends to zero given connecting the peripheries means adding them both (positive) first and (negative) second order links and adding just second order ones to the center.

5 Conclusions

In this paper we introduce network analysis in the theory of smoking behavior. In particular, starting from models of peer effects in a social network, we apply them to the specific case accounting for negative externalities (passive smoke). We thus model smoking behavior as a

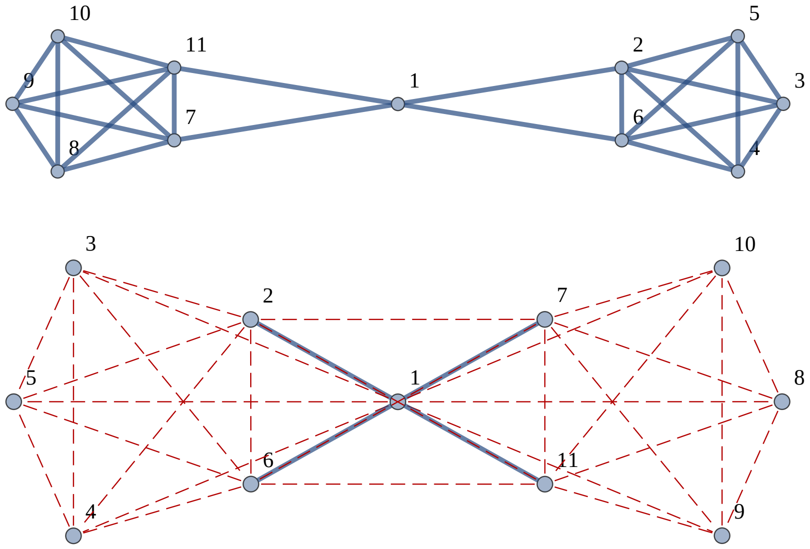


Figure 7: Ballester et al. (2006) case

result of different forces: how much people enjoy smoking, how much they like smoking together, how much they think active and passive smoke is dangerous for their health and how much they care about others' health. Starting from the case of regular networks we find a non trivial effect of the degree. In particular, at the equilibrium the quantity of smoking is a non monotone function of the degree, increasing for low degrees and decreasing for high ones. The same non monotone effect has been shown for the effect of policies aiming at reducing smoking prevalence, being them an increasing effect for low degrees and a decreasing effect for high degrees. We then introduce heterogeneity in tastes for smoking and we considered the effect of homophily on the equilibrium quantity in a regular network.We find that the homophily rete of a network does no affect the overall aggregate smoking intensity, while it affects its variance among agents. In particular, the spread between the smoking intensity of agents with a high taste for smoking and the smoking intensity of the agents with a low one is non monotone in the homophily rate. We then consider the case of a non regular network.

Appendix A: Utility Function

In this Appendix we give all the computations necessary in order to rewrite the utility function as in equation (3).

$$U_i = \alpha_i x_i + \sum_{j \in N} g_{ij} x_i x_j - \gamma_1 \delta \big[\gamma_0 x_i^2 + (\sum_{j \in N} g_{ij} x_j + x_i)^2\big] - \gamma_2 \delta \sum_{j \neq i} [\gamma_0 x_j^2 + (\sum_{k \in N} g_{jk} x_k + x_j)^2] \quad (9)$$

Now

$$\big[\gamma_0 x_i^2 + (\sum_{j \in N} g_{ij} x_j + x_i)^2\big] = \gamma_0 x_i^2 + x_i^2 + (\sum_{j \in N} g_{ij} x_j)^2 + 2 \sum_{j \in N} g_{ij} x_i x_j = (1+\gamma_0) x_i^2 + h + 2 \sum_{j \in N} g_{ij} x_i x_j$$

Consider the second part

$$\sum_{j \neq i} [\gamma_0 x_j^2 + (\sum_{k \in N} g_{jk} x_k + x_j)^2] = \sum_{j \neq i} \gamma_0 x_j^2 + \sum_{j \neq i} [\sum_{k \in N} g_{jk} x_k + x_j]^2 =$$

$$\sum_{j\neq i}\gamma_0 x_j^2+\sum_{j\neq i}[x_j^2+(\sum_{k\in N}g_{jk}x_k)^2+2\sum_{k\in N}g_{jk}x_jx_k]$$

$$\sum_{j\neq i}\gamma_0 x_j^2+\sum_{j\neq i}x_j^2+\sum_{j\neq i}(\sum_{k\in N}g_{jk}x_k)^2+2\sum_{j\neq i}\sum_{k\in N}g_{jk}x_jx_k$$

$$(1+\gamma_0)\sum_{j\neq i}x_j^2+\sum_{j\neq i}(\sum_{k\in N}g_{jk}x_k)^2+2\sum_{j\neq i}\sum_{k\in N}g_{jk}x_jx_k$$

Now, consider the second term

$$(\sum_{k\in N}g_{jk}x_k)^2=(\sum_{k\neq i}g_{jk}x_k+g_{ji}x_i)^2=(\sum_{k\neq i}g_{jk}x_k)^2+(g_{ji}x_i)^2+2\sum_{k\neq i}g_{jk}g_{ji}x_kx_i$$

so that

$$\sum_{j\neq i}(\sum_{k\in N}g_{jk}x_k)^2=\sum_{j\neq i}(\sum_{k\neq i}g_{jk}x_k)^2+\sum_{j\neq i}(g_{ji}x_i)^2+\sum_{j\neq i}2\sum_{k\neq i}g_{jk}g_{ji}x_kx_i=$$

$$=h_{-i}+d_ix_i^2+2\sum_{k\neq i}g_{ik}^{[2]}x_ix_k$$

and consider now the third term

$$2\sum_{j\neq i}\sum_{k\in N}g_{jk}x_jx_k=2\sum_{j\neq i}g_{ji}x_jx_i+2\sum_{j\neq i}\sum_{k\neq i}g_{jk}x_jx_k=2\sum_{j\neq i}g_{ij}x_ix_j+h_{-i}$$

Thus the utility is given by

$$U_i=\alpha_ix_i+\sum_{j\in N}g_{ij}x_ix_j-\gamma_i\delta\big[(1+\gamma_0)x_i^2+h+2\sum_{j\in N}g_{ij}x_ix_j\big]-$$

$$\gamma_2\delta\big[(1+\gamma_0)\sum_{j\neq i}x_j^2+h_{-i}+d_ix_i^2+2\sum_{k\neq i}g_{ik}^{[2]}x_ix_k+2\sum_{j\neq i}g_{ij}x_ix_j+h_{-i}\big]$$

so that

$$U_i=\alpha_ix_i+\sum_{j\in N}g_{ij}x_ix_j-\gamma_1\delta\big[(1+\gamma_0)x_i^2+2\sum_{j\in N}g_{ij}x_ix_j\big]-\gamma_2\delta\big[d_ix_i^2+2\sum_{k\neq i}g_{ik}^{[2]}x_ix_k+2\sum_{j\neq i}g_{ij}x_ix_j\big]+h_{-i}$$

$$U_i=\alpha_ix_i+(1-2\delta\gamma_1-2\delta\gamma_2)\sum_{j\in N}g_{ij}x_ix_j-\delta(\gamma_1(1+\gamma_0)+\gamma_2d_i)x_i^2-2\gamma_2\delta\sum_{k\neq i}g_{ik}^{[2]}x_ix_k+h_{-i}$$

$$U_i=\alpha_ix_i+(1-\Gamma_1-\Gamma_2)\sum_{j\in N}g_{ij}x_ix_j-\frac{1}{2}[\Gamma_1(1+\gamma_0)+\Gamma_2d_i]x_i^2-\Gamma_2\sum_{k\neq i}g_{ik}^{[2]}x_ix_k+h_{-i}$$

Appendix B: Γ_2 Threshold

Let us first consider the case of no altruism ($\Gamma_2 = 0$). Here, condition b. reduces to:

$$d < \frac{\Gamma_1(1+\gamma_0)}{(1-\Gamma_1)}. \tag{10}$$

Interpreting this condition, since the overall incentives to smoke increase with the degree d (since $(1-\Gamma_1) > 0$), only for low degrees these positive incentives balance the negative incentives due to the marginal damage of own active smoke (given by $\Gamma_1(1+\gamma_0)$). With altruism, things become more complex since the degree has a second opposite effect on incentives: the larger the degree, the larger the number of neighbours who are damaged (at the margin) from one's own smoke emissions. To identify the restriction on d imposed by condition b., let us first consider the roots of the LHS of b.:

$$\frac{(1-\Gamma_1) \pm \sqrt{(1-\Gamma_1)^2 - 4\Gamma_2\Gamma_1(1+\gamma_0)}}{2\Gamma_2}. \tag{11}$$

We obtain a positive equilibrium smoking for all positive degrees when the term inside the squared root is negative, that is when[7]:

$$\Gamma_2 > \Gamma_2^* \equiv \frac{(1-\Gamma_1)^2}{4\Gamma_1(1+\gamma_0)}. \tag{12}$$

Appendix C: Proof of Proposition 3

We need to prove only points 1) 2) and 3) of this proposition. We first consider point 1).

1) In order to prove the non monotonicity of marginal effects in d we study, in turn, the effect of policies on δ, γ_1 and γ_2.

I *Policy on δ.*

$$\frac{\partial x^*}{\partial \delta} = -\frac{2\alpha\big[(1+d+\gamma_0)\gamma_1 + d(1+d)\gamma_2\big]}{\big[\Gamma_2 d(1+d) - d(1-\Gamma_1) + \Gamma_1(1+\gamma_0)\big]^2} < 0;$$

As expected, a better awareness of the health hazard of smoking decreases smoking intensity. The magnitude of the effect of δ changes with the degree d. Now, if $d = 0$ then $\frac{\partial x^*}{\partial \delta} < 0$ and for $d \to \infty$ then $\frac{\partial x^*}{\partial \delta} \to 0$. So that in the range of positive d there should be a null or a positive odd number of maxima and/or minima. If d is very negative (not a real case, but just to understand the shape of the function) $\frac{\partial x^*}{\partial \delta} > 0$ and if $d \to -\infty$ then $\frac{\partial x^*}{\partial \delta} \to 0$ so that a positive odd number of maxima/minima are shown. However there are no more than 3 overall maxima/minima, since:

$$\frac{\partial^2 x^*}{\partial \delta \partial d} = \frac{4\alpha\delta(\gamma_1 + \gamma_2(1+2d))(\gamma_1(1+d+\gamma_0) + \gamma_2 d(1+d)) - 2\alpha[(2+d+2\gamma_0)\gamma_1 + d\gamma_2]}{\big[\Gamma_2 d(d+1) - d(1-\Gamma_1) + \Gamma_1(1+\gamma_0)\big]^3}.$$

If $x^* > 0$ the parametrization is such that the denominator is always positive. The numerator is of third degree in d thus $\frac{\partial x_i}{\partial \delta}$ has at most 3 maxima/minima. Noting that if $\Gamma_1 + \Gamma_2 < 1$ then

[7] Note that this condition is consistent with the reasonable restriction $\Gamma_2 < \Gamma_1$, requiring that one cares for his own health more than for the health of others. To respect this additional restriction, we need to impose that $\Gamma_2^* - \Gamma_1 < 0$. This expression is decreasing in Γ_1, and has root $\Gamma_1^* = \frac{2\sqrt{\gamma_0+1}-1}{4\gamma_0+3}$. We conclude that $\Gamma_2^* < \Gamma_1$ for all $\Gamma_1 > \frac{2\sqrt{\gamma_0+1}-1}{4\gamma_0+3} > 0$.

$\frac{\partial^2 x^*}{\partial\delta\partial d}|_{d=0} < 0$, it turns out that there should be only one minimum for $d > 0$.
Thus we can state that an increase in δ always reduce the prevalence of smoke. This effect is non monotone in d and in particular is increasing, in absolute terms, for low levels of d, reaches a peak and then constantly decreases, in absolute terms, with an increasing d.

II *Policy on* γ_1.

$$\frac{\partial x^*}{\partial\gamma_1} = -\frac{2\alpha\delta(d+1+\gamma_0)}{\left[\Gamma_2 d(d+1) - d(1-\Gamma_1) + \Gamma_1(1+\gamma_0)\right]^2};$$

and

$$\frac{\partial^2 x^*}{\partial\gamma_1\partial d} = \frac{2\alpha\delta\left\{3d^2\Gamma_2 - (1+\gamma_0)(2-\Gamma_1-2\Gamma_2) + d(\Gamma_1+\Gamma_2(5+4\gamma_0))\right\}}{\left[\Gamma_2 d(1+d) - d(1-\Gamma_1) + \Gamma_1(1+\gamma_0)\right]^3}$$

Thus we have that $\frac{\partial x^*}{\partial\gamma_1} < 0$ always, moreover in $d = 0$ we have that $\frac{\partial x^*}{\partial\gamma_1} < 0$ and for $d \to \infty$ we have that $\frac{\partial x^*}{\partial\gamma_1} \to 0$. Since there are only two possible maxima/minima and, if $\Gamma_1 + \Gamma_2 < 1$ it is that $\frac{\partial^2 x^*}{\partial\gamma_1\partial d}|_{d=0} < 0$, then there exists only one minimum in $d > 0$. Thus, in this case too the effect of an increase in γ_1 is always to reduce the prevalence of smoking. This effect is non monotone in d and is increasing for low levels of d, it reaches a peak and decreases.

III *Policy on* γ_2.

$$\frac{\partial x^*}{\partial\gamma_2} = -\frac{2\alpha\delta d(1+d)}{\left[\Gamma_2 d(1+d) - d(1-\Gamma_1) + \Gamma_1(1+\gamma_0)\right]^2} < 0$$

$$\frac{\partial x^*}{\partial\gamma_2\partial d} = \frac{\Gamma_2 d(1+d(1+2d)) - \Gamma_1(1+d+\gamma_0(1+2d)) - d}{\left[\Gamma_2 d(1+d) - d(1-\Gamma_1) + \Gamma_1(1+\gamma_0)\right]^3}$$

Thus, if $d > 0$ then $\frac{\partial x^*}{\partial\gamma_2} < 0$, if $d \to \pm\infty$ then $\frac{\partial x^*}{\partial\gamma_2} = 0$ and, finally, $\frac{\partial x^*}{\partial\gamma_2\partial d}|_{d=0} < 0$. Consequently only one minimum is feasible in $d > 0$. Thus, in this case too the effect of an increase in γ_2 is always to reduce the prevalence of smoking. This effect is increasing for low levels of d, it reaches a peak and then decreases.

2) By comparing the numerators of $\frac{\partial x^*}{\partial\gamma_1}$ and $\frac{\partial x^*}{\partial\gamma_2}$ the result immediately follows

3) Consider the comparison between a policy on δ and a policy on γ_2.

$$|\frac{\partial x_i}{\partial\delta}| > |\frac{\partial x_i}{\partial\gamma_2}| \iff d^2(\gamma_2-\delta) + d(\gamma_1+\gamma_2-\delta) + \gamma_1(1+\gamma_0)$$

with roots

$$d = \frac{-(\gamma_1+\gamma_2-\delta) \pm \sqrt{(\gamma_1+\gamma_2-\delta)^2 - 4\gamma_1(1+\gamma_0)(\gamma_2-\delta))}}{2\gamma_2}$$

Now, if $\gamma_2 > \delta$ the condition is always satisfied. If, on the contrary, $\delta > \gamma_2$, the function is concave and then the largest root is positive; so, a policy on δ has a higher marginal effect than a policy on γ_2 only for small enough d.

Appendix D: Marginal effects of different policies on equilibrium smoking

In this Appendix we study, for completeness all the remaining marginal effects and we perform some comparisons.

I *Policy on α.*

$$\frac{\partial x^*}{\partial \alpha} = \frac{1}{\left[\Gamma_2 d(1+d) - d(1-\Gamma_1) + \Gamma_1(1+\gamma_0)\right]}.$$

The effect of this policy is linear in α so that the level of the private enjoyment of smoking parameter does not change the marginal effectiveness of this policy. In the same time we have that

$$\frac{\partial^2 x^*}{\partial \alpha \partial d} = \frac{1 - 2\delta(\gamma_1 + 2(d+1)\gamma_2)}{\left[\Gamma_2 d(1+d) - d(1-\Gamma_1) + \Gamma_1(1+\gamma_0)\right]^2}$$

and thus

$$\frac{\partial^2 x^*}{\partial \alpha \partial d} > 0 \Leftrightarrow d < \frac{1 - \Gamma_1 - \Gamma_2}{2\Gamma_2}.$$

Consequently a policy aiming at marginally reducing the smoke preference parameter is non monotone in the degree, having an increasing effect, in absolute values, for low degrees and a decreasing effect, in absolute terms, for high degree. The effectiveness peak is reached for $d = \frac{1-\Gamma_1-\Gamma_2}{2\Gamma_2}$. Thus the higher the altruistic concerns the lower the degree level at which the policy has the highest effectiveness. In the same the higher the concerns for own health the lower this degree threshold.

II *Policy on γ_0.*

$$\frac{\partial x^*}{\partial \gamma_0} = -\frac{\alpha \Gamma_1}{\left[\Gamma_2 d(1+d) - d(1-\Gamma_1) + \Gamma_1(1+\gamma_0)\right]^2} < 0$$

We now study how this effect changes with the density of the network. Note that:

$$\frac{\partial x^*}{\partial \gamma_0 \partial d} = \frac{2\alpha\Gamma_1\big((1+2d)\Gamma_2 + \Gamma_1 - 1\big)}{\left[\Gamma_2 d(d+1) - d(1-\Gamma_1) + \Gamma_1(1+\gamma_0)\right]^3}$$

Thus, the marginal effect of the policy is always negative, it is decreasing when $d = 0$ and is 0 if d reaches ∞, so that it has a minimum in $d = \frac{1-\Gamma_1-\Gamma_2}{2\Gamma_2}$.This means that an increase in γ_0 has a non monotone marginal effect on equilibrium smoking and, in particular, the reduction reaches its peak when $d = \frac{1-\Gamma_1-\Gamma_2}{2\Gamma_2}$.

III *Comparisons on δ policies* Consider the comparisons between δ and γ_i policies.

$$|\frac{\partial x_i}{\partial \delta}| > |\frac{\partial x_i}{\partial \gamma_0}| \iff (1 + d + \gamma_0 - \delta)\gamma_1 + d(1+d)\gamma_2 > 0$$

Now, this is a quadratic function that has roots

$$d = \frac{-\gamma_1 - \gamma_2 \pm \sqrt{\gamma_1^2 + \gamma_2^2 - 2\gamma_2\gamma_1(1 + 2\gamma_0 - 2\delta)}}{2\gamma_2}$$

Now if $1 + 2\gamma_0 - 2\delta > 0$ then $d_{1,2} < 0$ and the condition is always satisfied. If $1 + \gamma_0 - \delta < 0$ then $d_2 > 0$ and the condition is satisfied only of d large, namely $d > d_2$.

In the same way consider now the following:

$$|\frac{\partial x_i}{\partial \delta}| > |\frac{\partial x_i}{\partial \gamma_1}| \iff d^2\gamma_2 + d(\gamma_1 + \gamma_2 + \delta) + (1+\gamma_0)(\gamma_1 + \delta) > 0$$

with roots

$$d = \frac{-(\gamma_1 + \gamma_2 - \delta) \pm \sqrt{(\gamma_1 + \gamma_2 - \delta)^2 - 4\gamma_2(1+\gamma_0)(\gamma_1 - \delta))}}{2\gamma_2}$$

Now, if $\gamma_1 > \delta$ the same argument as before holds and the condition is always satisfied. If, on the contrary, $\delta > \gamma_1$ then the largest root is positive, so that given any δ a policy on δ has a higher marginal effect than a policy on γ_1 only for largest enough d.

III *Comparisons on α Policies*

$$|\frac{\partial x_i}{\partial \alpha}| > |\frac{\partial x_i}{\partial \delta}| \Leftrightarrow \alpha < \frac{\Gamma_1(1+d+\gamma_0) + \Gamma_2 d(1+d) - d}{2\gamma_1(1+\gamma_0+d) + 2d(1+d)\gamma_2} \equiv \alpha_\delta$$

$$|\frac{\partial x_i}{\partial \alpha}| > |\frac{\partial x_i}{\partial \gamma_0}| \Leftrightarrow \alpha < \frac{\Gamma_1(1+d+\gamma_0) + \Gamma_2 d(1+d) - d}{\Gamma_1} =\equiv \alpha_{\gamma_0}$$

$$|\frac{\partial x_i}{\partial \alpha}| > |\frac{\partial x_i}{\partial \gamma_1}| \Leftrightarrow \alpha < \frac{\Gamma_1(1+d+\gamma_0) + \Gamma_2 d(1+d) - d}{2\delta(1+d+\gamma_0)} \equiv \alpha_{\gamma_1}$$

$$|\frac{\partial x_i}{\partial \alpha}| > |\frac{\partial x_i}{\partial \gamma_2}| \Leftrightarrow \alpha < \frac{\Gamma_1(1+d+\gamma_0) + \Gamma_2 d(1+d) - d}{2\delta d(1+d)} \equiv \alpha_{\gamma_2}$$

Appendix E. Proof of proposition 4

We need to prove that $x^H > x^L$ in equilibrium and that when $d < d^*$ the spread is monotonically increasing in d.

First of all notice that we focus only on cases in which each agent smokes a positive quantity of smoke, so that the average smoke is positive. This happens only if the denominator of the first part of the solution is positive, so that if

$$\Gamma_1\big(1+\gamma_0\big) - d\big(1-\Gamma_1\big) + \Gamma_2 d^2 > 0$$

Now, L agents smoke more than H agents only if the denominator of the second part of the solution is negative, so that

$$x^L > x^H \text{ } if \text{ } and \text{ } only \text{ } if \text{ } D \equiv \Gamma_1\big(1+\gamma_0\big) + \Gamma_2 d^2\big(1-2q\big)^2 + d\big(1-2q\big)\big(1-\Gamma_1\big) < 0$$

Notice that this condition can be satisfied only if $q > \frac{1}{2}$. Now, $D(q = \frac{1}{2}) = \Gamma_1(1+\gamma_0) > 0$ and is decreasing in $q \in (\frac{1}{2}, \bar{q})$. Then D is increasing for $q > \bar{q}$. However in $q = 1$ we have that $D = \Gamma_1(1+\gamma_0) + d^2\Gamma_2 - d(1-\Gamma_1) > 0$. Thus, if we prove that $D(\bar{q}) > 0$, then it always happens that $x^H > x^L$. Now

$$D(\bar{q}) = \frac{-1 + 2\Gamma_1 - \Gamma_1^2 + 4\Gamma_1\Gamma_2(1+\gamma_0)}{4\Gamma_2}$$

This is positive if and only if

$$\Gamma_2 > \frac{(1-\Gamma_1)^2}{4\Gamma_1(1+\gamma_0)}$$

This, however, is exactly the condition (12) we have on the positivity of the smoke level under homogenous player. Since the equilibrium level under homogenous level is the average smoke level in this framework, the same positivity condition holds here. Thus it always happens that $D > 0$ and consequently it is always that $x^H > x^L$.

It now remains to prove that if $d < d^*$ then the spread is monotone in q. Notice that the spread is increasing in q when $\bar{q} > 1$. Now, $\bar{q} > 1$ exactly if and only if $d < d^*$.

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